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ASPECTS OF ELECTRIC FIELD PROFILES AND TOTAL LIGHTNING IN SEVERE THUNDERSTORMS IN STEPS

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1. INTRODUCTION

During the Severe Thunderstorm Electrification and Precipitation Study (STEPS) in the area of Goodland, Kansas, in 2000, we made balloon-borne soundings of the electric field, E, in coordination with observations from a three-dimensional, total lightning mapping system, and polarimetric radars. A primary goal of STEPS was to understand why many severe storms produce positive, instead of the more usual negative, cloud-to-ground flashes. Another was to document the lightning and electrification of the storms characteristic of the drier climate of the High Plains, which had not been described systematically before. Electric field profiles, three-dimensional lightning mapping data, and polarimetric radar were among the data collected from both severe and non-severe storms and from one mesoscale convective system. (For information on STEPS, see http:// www.mmm.ucar.edu/community/steps.html.)

The lightning mapping array observed a number of storms in which the intracloud lightning flashes were inverted in polarity, namely between midlevel positive charge and upper level negative charge. We report here on the search for a correspondence between the inverted-polarity cloud flashes and the charge structure in the storm as inferred from the electric field profile. The electrical charge structure of a few storms, inferred from the electric field profile, indicates that there are storms in which the electrical structure is inverted.

We acquired usable electric field profiles from twenty-three balloon flights. Our analyses are ongoing, though we have early results to report. Our preliminary analyses in collaboration with other STEPS scientists have yielded the following results that impact the understanding of storm electrification.

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2. EFFECTS OF STRONG UPDRAFTS ON A STORM'S CHARGE DISTRIBUTION

The electric field profile in strong updrafts, including mesocyclones, indicates an absence of charge in the lower part of the updraft region. We obtained a few soundings in mesocyclones to supplement the one sounding with lightning mapping data we had obtained in central Oklahoma during MEaPRS 1998. In all cases in which the balloon was in strong updrafts in a mesocyclone, significant charge density was absent below a height ≈8 km MSL, in agreement with the mesocyclone effect hypothesized by MacGorman et al. (1989). Furthermore, we found that outside the mesocyclone, charge was present at the lower altitudes where it is usually observed. An initial hypothesis, needing testing by modeling studies, with additional electric field profiles and polarimetric radar data, is that the strong updraft shifts graupel formation to higher altitudes, and the vorticity and strong upper-level divergence combine to interfere with recirculation of graupel into the updraft. Together these two effects prevent charge from occurring at lower altitudes in mesocyclone updrafts.

3. INVERTED-POLARITY STORM CHARGE AND LIGHTNING

By inverted-polarity storm (more specifically, inverted-polarity electrical structure) we mean that the normal polarities of charge in two or more vertically separated regions of a storm are reversed. The most direct measurements of the vertical electrical structure of thunderstorms have been electric field profiles obtained from balloon-borne instruments. Because looking for inverted structures in these data requires knowledge of typical (i.e., noninverted) thunderstorm structures, we summarize present knowledge of typical structures. Based largely on profiles of E_z, the vertical component of E, estimated from corona current by Simpson and Robinson (1941), the classic view of the gross electrical structure of a thunderstorm has been that it is a 'tripole': a main positive charge above a main negative charge above a smaller lower positive charge. Balloon soundings of electric field obtained during the last two decades indicate that the vertical structure is usually more complex than this, with a smaller negative charge typically above the upper positive charge and sometimes more charge regions in the lower part of the thunderstorm (Stolzenburg et al. 1998). Modeling studies have also indicated more charge regions in the lower part of the storm, e.g., Ziegler and MacGorman (1994).

Cloud flashes in storms with a normal charge distribution typically occur between the upper positive region and the midlevel negative region below it. Cloud-to-ground flashes are typically between the midlevel negative region and ground.

The possibility that anomalous charge distributions exist has been offered as a hypothesis (e.g., Williams 1989, Rutledge et al. 1993) to explain a growing body of evidence that all or most of the cloud-to-ground lightning flashes during extensive periods of some storms lower positive charge to ground, instead of the usual negative charge (e.g., Rust et al. 1981, MacGorman and Burgess 1994).

The first evidence that the polarity of cloud flashes in the upper part of storms can be inverted from normal was obtained with the lightning mapping system in central Oklahoma in 1998 in the MEaPRS field program. Many additional storms producing inverted-polarity lightning were observed in STEPS, providing increased evidence for inverted charge distributions from the lightning mapping array (Krehbiel et al. 2000). The inverted-polarity discharges are characterized by downward rather than upward initial development in the located radiation sources and have a bilevel structure indicative of breakdown between upper negative and midlevel positive charge regions, rather than the other way around.

The initial electric-field evidence that the gross electrical structure of a storm can be inverted comes from the electric field profiles such as the example in Figure 1 (left panel) to which Rust and MacGorman (2002) applied a one-dimensional approximation of Gauss's law to infer the vertical sequence of charges (shown in the figure).

As we further examine the STEPS data, part of what we are attempting is to extract more information from the electric field profile. To do this, we are comparing the charge structure from Gauss's law with that inferred in plots of the electric field vector. We have developed techniques for extracting the full vector electric field from the data and are working on ways to plot and interpret these data relative to lightning structure and radar-derived storm parameters. For example, Figure 2 shows the vector electric field in a vertical cross section of the same storm as in Figure 1. The vectors suggest that most of the charge is to the right of the balloon track and indicate a layer of positive charge near 7.5 km MSL and a layer of negative charge above that. This analysis does not yield the lowest and highest charge regions inferred by applying Gauss's law. However, the charge distributions inferred from both analyses would be considered inverted.

The first issue for future research is to further test the hypothesis that inverted-polarity electrical structures exist, though the present evidence seems strong. To enhance the electric field sounding data, we are upgrading the balloon-borne electric field meter to provide higher resolution and more accurate directional data to use in determining electric field vectors.

Several mechanisms have been suggested for producing inverted-polarity charge distributions and lightning. For example, (Lyons et al. 1998) have suggested that microphysical properties could be modified by smoke particle ingestion into the cloud to change significantly the charge distribution and thereby affect the polarity of lightning that occurs. Laboratory experiments suggest that the polarity of charge transferred to graupel is reversed from normal during collisions when liquid water content is large (e.g., Takahashi 1978, Jayaratne et al. 1983). Thus, unusually large amounts of liquid water in the mixed phase region might be expected to invert the charge distribution. Evidence that this behavior may occur in one storm is presented at this conference by MacGorman et al. (2002). Such microphysical behavior should be detectable in other storms if it is responsible for this lightning behavior. However, the lightning mapping observations can be interpreted as indicating that the inverted-polarity electrification comes about in a more complex manner that would not be explained by increased liquid water content alone (Krehbiel 2001).

4. COMPARISON OF STORM CHARGE STRUCTURE AND INTRACLOUD LIGHTNING POLARITY

Comparison of the electric field profile and inferred charge structure of storms is also being made with the charge regions inferred from the lightning mapping data, such as is shown in Figure 1 (right panel). In this example, the lightning-inferred charge regions (the area of black dots) slope downward from the radar core. The parts of the charge regions closest to the flight track of the balloon align in altitude with the same polarity of charge inferred from Gauss's law and the electric field vector display. Each region of lightning activity

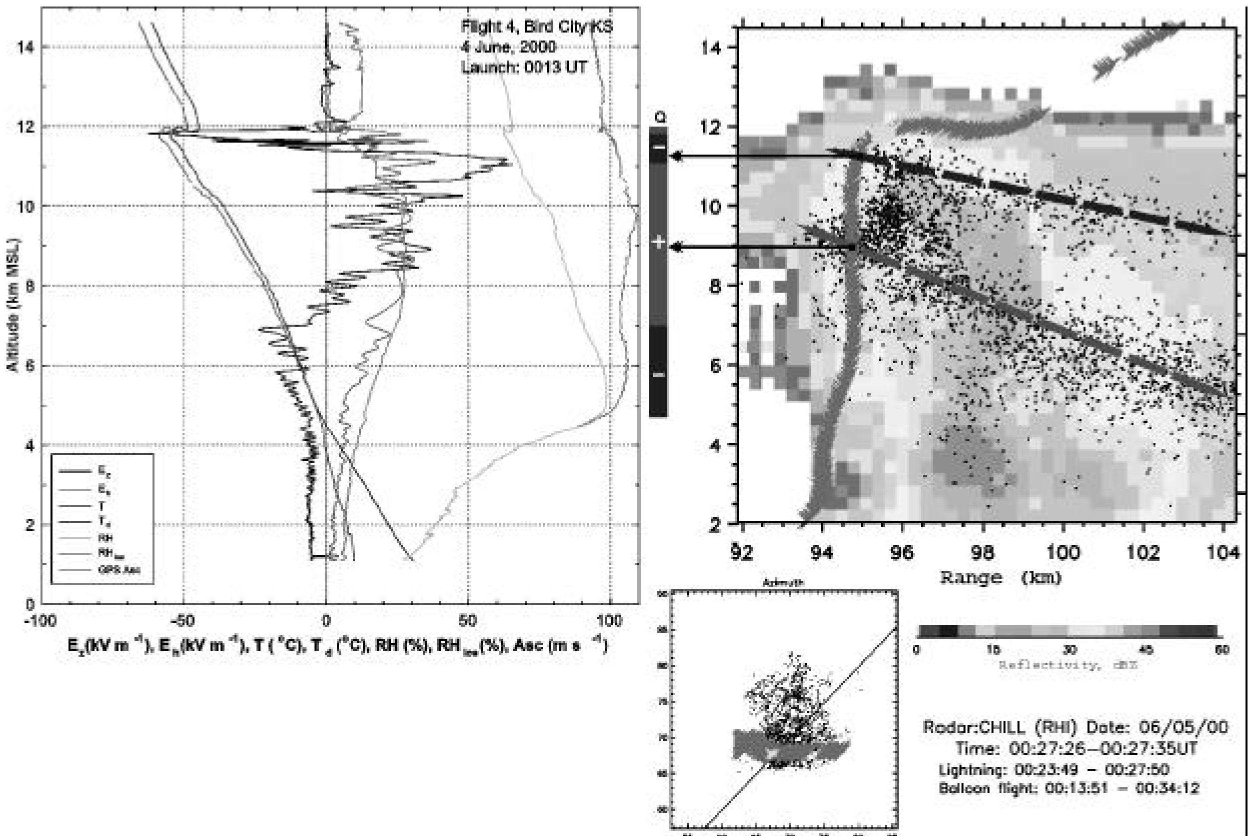

Figure 1. Sounding in an isolated storm during STEPS. The inferred charge layers are the vertical bars, Q, to the right of the sounding graph. The dots on the radar RHI show 4 min of lightning mapping data in the storm. The dashed lines depict the approximate center of the lightning sources in the upper and lower levels of the discharges. The lightning data suggest the upper charge is negative and the lower charge positive. The horizontal arrows indicate the heights of these two charge regions relative to the inferred charge from E_z. The balloon track is the broad nearly vertical line to the left of the core until it goes over the core at about 12 km.

tends to occur in and near a charge region inferred from the electric field sounding, as has been hypothesized. The lightning- and electric field - inferred charge regions sometimes exhibit differences that could arise from horizontal nonuniformity or the space-time nature of the sounding measurements. This will be a complex analysis task, which is just beginning.

In conclusion, we continue to test the hypothesis that inverted-polarity electrical structures exist in thunderstorms and to analyze storms to look for relationship between lightning-inferred charge structure and that from the electric field profiles.

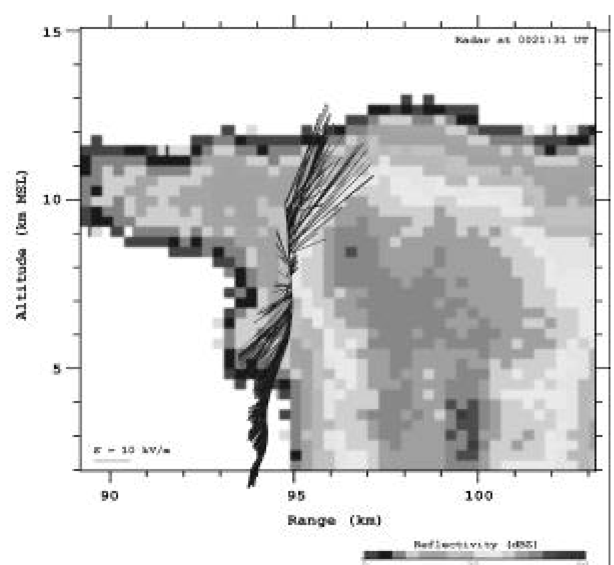

Figure 2. Components of the vector E along the balloon track from 0-10 km and in the plane of the RHI reflectivity from CSU-CHILL. The vector scale is shown in lower left. This is the same storm as in Figure 1.

Acknowledgments. We thank Dennis Nealson and Sherman Fredrickson for help preparing the mobile labs and the many–too numerous to list--who have helped us acquire the data and analyze it. We appreciate those who developed software tools: Doug Kennedy, Aaron Bansemer, Demian Shown, and Kyle Wiens. This research was supported by NSSL, the Cooperative Institute for Mesoscale Meteorological Studies of the University of Oklahoma, and in part by NSF grants ATM-9807179 and ATM-9912562 to the University of Oklahoma/Cooperative Institute for Mesoscale Meteorology Studies, and ATM- 9912073 to New Mexico Tech.

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